Heteroepitaxy of deposited amorphous layer by pulsed electron-beam irradiation

S. S. Lau, W. F. Tseng, M-A. Nicolet, and J. W. Mayer

California Institute of Technology, Pasadena, California 91125

J. A. Minnucci and A. R. Kirkpatrick

Spire Corporation, Bedford, Massachusetts 01730
(Received 10 April 1978; accepted for publication 29 May 1978)

We demonstrate that a single short pulse of electron irradiation of appropriate energy is capable of recrystallizing epitaxially an amorphous Ge layer deposited on either ⟨100⟩ or ⟨111⟩ Si single-crystal substrate. The primary defects observed in the ⟨100⟩ case were dislocations, whereas stacking faults were observed in ⟨111⟩ samples.

PACS numbers: 73.40.Lq, 81.10.Jt, 68.55.+b, 61.70.−r

Electron-beam pulse annealing has recently been applied to the manufacturing of Si solar cells.[1] The solar-cell junction is introduced by ion implantation with the proper dopant. The amorphous and/or damaged Si layer due to ion implantation is then completely recrystallized by a short single pulse of an electron beam. Solar cells with efficiencies higher than 10% are manufactured by this technique.

In concept, electron-beam pulse annealing is very similar to the laser-irradiation technique where a short pulse of intense energy is incident on the sample surface. The absorbed energy in the sample causes a high-temperature spike. The subsequent fast relaxation of the thermal spike creates sufficient undercooling near the original amorphous-crystalline interface to induce epitaxial crystal growth.

In a previous investigation,[2] we have demonstrated that amorphous Si layers deposited onto single-crystal wafers in a conventional vacuum chamber ($\sim 1\times10^{-6}$ Torr during evaporation, and without sputter cleaning or high-temperature decomposition) can be recrystallized epitaxially by pulsed laser irradiation. In this study, we report the possibility of electron-beam pulse annealing for epitaxial growth of heterostructure (thin Ge layer on Si substrate).

Si single-crystal substrates, ⟨100⟩ and ⟨111⟩ oriented, were first degreased in organic solvents and then immersed in a dilute HF solution. The samples were then rinsed in high-purity water and immediately loaded in an evaporation chamber equipped with ion pumps. Amorphous Ge layers 2000–3000 Å thick were evaporated onto the substrates at a rate of ~30 Å/sec at pressures of $(1-2)\times10^{-7}$ Torr. No high temperature or sputter cleaning of the wafer was applied before the deposition, nor were intentional dopants of any kind evaporated.

The samples were then irradiated by a short pulse of electron irradiation in vacuum.[1] The mean electron

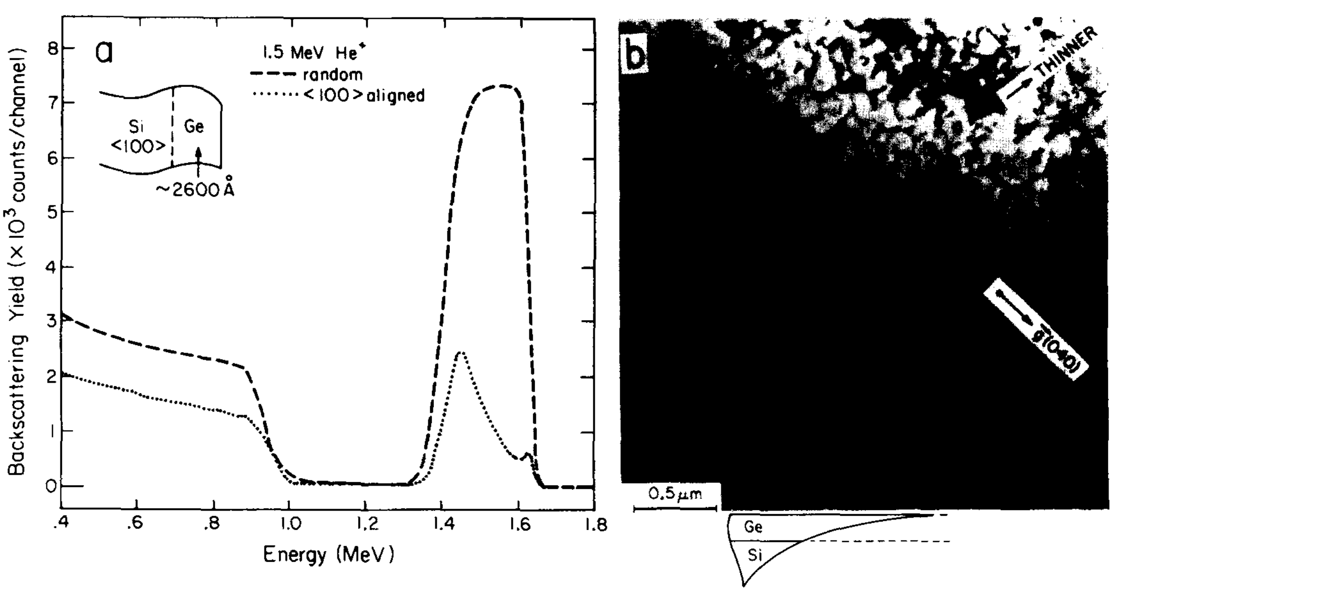

FIG. 1. (a) Backscattering spectra of a sample after electron-beam irradiation. The sample consisted of an amorphous Ge layer (~2600 Å) evaporated on a ⟨100⟩ Si wafer. The dashed line denotes the spectrum when the analyzing beam impinges on the sample in a random direction, whereas the dotted line (solid circles) denotes the spectrum when the beam is aligned with the ⟨100⟩ direction of the Si substrate. (b) TEM micrograph showing dislocations in the ⟨100⟩ sample for (a).

energy was about 20 keV with a maximum energy less than 125 keV, the threshold for lattice displacement damage in Si. The duration of the electron pulse was approximately 10^{-7} sec. The delivered energy of the electrons was about 0.8 J/cm^2. The electron-beam diameter was about 5 cm. After exposure to single pulses of electron irradiation, the samples were examined by MeV He ion channeling and transmission electron microscopy.

It was found that a layer of 2600 Å evaporated Ge transformed into an epitaxial layer on either ⟨100⟩ or ⟨111⟩ Si substrate by a single pulse of electron-beam irradiation. Figure 1(a) shows the backscattering spectra for a ⟨100⟩ sample after electron-beam irradiation under random and aligned conditions. The dashed line denotes the backscattering spectrum when the analyzing beam (1.5 MeV, beam diameter ~1 mm) was incident on the sample in a random direction and the closed circles denote the channeled backscattering spectrum when the analyzing He ion beam was aligned with the ⟨100⟩ direction of the substrate. The reduction in the backscattering yield from the Ge layer (the signal centered around 1.6 MeV) indicates that the amorphous Ge layer has transformed into an epitaxial layer. The minimum yield near the surface (χ_{min}) is ~6.5% and increases to ~37% near the Ge/Si interface. This increase in the channeling yield is indicative of the presence of defects in the epitaxial layer. This observation is rather common in heteroepitaxy where an epitaxial layer is grown on a substrate of different material with a different lattice parameter, as in the case of Si layers epitaxially grown on sapphire ($1\bar{1}02$) substrates.[3] The origin of these defects is basically due to the lattice mismatch between the substrate and the epitaxial layer. Figure 1(b) shows a transmission electron micrograph of the same sample shown in Fig. 1(a). The defects observed in ⟨100⟩-oriented samples are primarily dislocations. The (100) projected dislocation density, as measured from Fig. 1(b) is about 4×10^5 cm/cm^2 in unit of length per area. The projected line directions of dislocations are generally found to lie along either ⟨011⟩ or ⟨021⟩ directions. Dislocations with extinction fringes seem to incline along the ⟨112⟩ direction. The majority of dislocations are identified to be of the edge type by the standard Burgers vector determination. A few dislocations in curved shape are of the mixed type.

Figure 2(a) shows the backscattering spectra for a ⟨111⟩ sample after electron irradiation under random and aligned condition. The epitaxial nature of the Ge layer is clearly demonstrated by the reduction of the backscattering yield (closed circles) when the analyzing He beam is aligned with the ⟨111⟩ axis of the substrate. The minimum yield near the surface is about 13% and increases to about 60% near the Ge/Si interface. These channeled yields are higher than those obtained on ⟨100⟩ samples. Figure 2(b) shows a bright-field transmission electron micrograph of the sample after electron irradiation. The crystalline imperfections, in this case, are primarily intrinsic stacking faults. It is interesting to note that the misfit strain was relaxed by dislocations in the ⟨100⟩ case, whereas it was relaxed by stacking faults and partial dislocations in the ⟨111⟩ heteroepitaxy. In laser annealing of amorphous layers formed by implantation of Si ions into crystalline Si, stacking faults were found in ⟨111⟩-oriented Si, but not ⟨100⟩-oriented crystals[4] (at an energy density of ~2.5 J/cm^2 ruby Laser, Q switched). This indicates that stacking faults are not only related to hetero-epitaxy, but also to the orientation of the substrates.

From the gradual slopes of the Si (front edge) and Ge (rear edge) signals in the backscattering spectra obtained in the random direction, there seemed to be some interdiffusion between the Si and Ge due to elec-

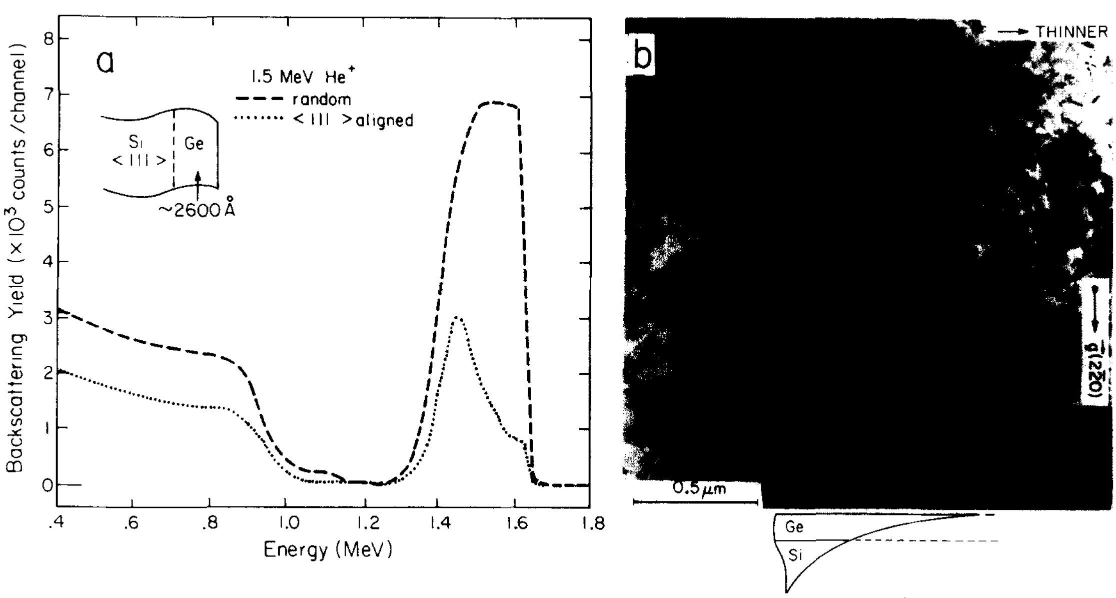

FIG. 2. (a) Backscattering spectra of a sample consisted of an amorphous Ge (~2600 Å) deposited on ⟨111⟩ Si substrate. (Dashed line—spectrum in random direction; dotted line—⟨111⟩ aligned spectrum). (b) TEM micrograph showing stacking faults in the ⟨111⟩ sample for (a). The micrograph was taken at the two-beam condition with one of 220 spots diffracted. Under this condition, the stacking faults lying on one of three inclined (111) planes did not show up in this micrograph.

TABLE I. Characteristics of epitaxial Ge layers on ⟨100⟩ and ⟨111⟩ Si wafers induced by electron-beam irradiation.

	⟨100⟩	⟨111⟩
χ_{min} near Ge surface	~ 6.5%	~13%
χ_{min} near Ge/Si interface	~37%	~60%
Primary defects in epitaxial Ge layer	Dislocations (~ 4×10^5 cm/cm^2)	Stacking faults
Ge surface after irradiation	Flat	Slightly wavy
Interface	Not abrupt	Some interdiffusion

tron-beam irradiation. This was more prominantly observed on the ⟨111⟩ sample. Scanning electron and optical microscopic studies on these samples indicated that the ⟨111⟩ Ge/Si surface was slightly wavy and the ⟨100⟩ Ge/Si surface was essentially flat. The waviness of the sample surface could also contribute to the gradual slopes of the backscattering signals. The characteristics of the Ge epitaxial layers on ⟨100⟩ and ⟨111⟩ Si wafers are tabulated in Table I.

In summary, we demonstrate that a single pulse of electron-beam irradiation of sufficient energy is capable of recrystallizing a Ge layer (~2600 Å) deposited on either ⟨100⟩ or ⟨111⟩ Si wafers into an epitaxial layer. The deposition was carried out in a dry pumping chamber (~10^{-6}–10^{-7} Torr) without the use of sputter cleaning and/or high temperature decomposition of the substrate surface.

We believe the same technique can be used on other types of heteroepitaxy such as Ge on GaAs.

The Caltech group acknowledges the partial financial support of the Office of Naval Research (L. Cooper).

[1]A.R. Kirkpatrick, J.A. Minnucci and A.C. Greenwald, IEEE Trans. Electron Devices **ED-24**, 429 (1977).
[2]S.S. Lau, W.F. Tseng, M-A. Nicolet, J.W. Mayer, R.C. Eckardt, and R.J. Wagner, Appl. Phys. Lett. (to be published).
[3]S.T. Picraux and G.J. Thomas, J. Appl. Phys. **44**, 594 (1973).
[4]G. Foti, E. Rimini, W.F. Tseng, and J.W. Mayer, Appl. Phys. **15**, 365 (1978).